Performance Limiting Defects in SiC Based Transistors

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ABSTRACT

We have combined very sensitive electron paramagnetic resonance measurements and electrical measurements to identify performance limiting defects in SiC based semiconductor devices. This work is relevant to the US Army because SiC based devices offer quite significant potential advantages for high power and high temperature electronics.

INTRODUCTION

Silicon carbide (SiC) has numerous potential material advantages over silicon for the development of high-temperature, high-voltage solid-state power devices, including a wide bandgap, large critical field, and large thermal conductivity (Neudeck, 2000; Zopher, Skowronski, 2005). The intrinsic properties of SiC can lead to compact power switches in hybrid-electric vehicle motor drives for the FCS; replacing Si with SiC can lead to systems with less weight, less volume, and increased functionality. The preferred power switch is the SiC MOSFET, a normally-off voltage-controlled device. The performance and reliability of SiC based devices is typically far less than optimum because of as yet poorly understood atomic scale defects.

A collaborative Penn State-US Army Research Laboratory effort under the Power and Energy CTA has combined electrical measurements and very sensitive electrically detected magnetic resonance (EDMR) measurements to identify performance limiting defects in SiC based metal oxide semiconductor field effect transistors (MOSFETs) and SiC based bipolar junction transistors (BJTs). The focus has been upon those defects which have the greatest impact on performance: SiC/SiO_2 interface and near interface defects in the MOSFET and recombination centers in the BJTs. The EDMR measurements utilize spin-dependent recombination (SDR), a very sensitive electron spin resonance (ESR) technique which allows identification of the physical and chemical nature of defects in semiconductor devices (Lepine, 1972; Kaplan et al., 1978; Lenahan, Jupina, 1990).

Conventional electron spin resonance (ESR) studies have been utilized to identify defects within 4H SiC materials (Mizuochi et al., 2003, 2005; Wimbauer et al., 1997; Itoh et al., 1997; Cha et al., 1998) but it does not have the sensitivity to observe defects in semiconductor devices. The electrically detected ESR technique, spin dependent recombination (SDR), has about seven orders of magnitude higher sensitivity and thus can be applied for ESR study of transistors (Lenahan, Jupina, 1990).

SDR exploits the fact that recombination in semiconductors is spin dependent (Lepine, 1972; Kaplan et al., 1978). The measurements are made by configuring a device in such a way that the device current is dominated by recombination events. By simultaneously exposing the device to a large magnetic field H and microwave irradiation of frequency ν, one can observe ESR of the deep level recombination center by monitoring the response of the recombination current versus magnetic field. The SDR field-frequency-current response is virtually identical to the ESR spectrum of the defect under observation. In the simplest of cases, the ESR magnetic resonance condition is given by $h\nu = g\beta H$, where h is Planck's constant, β is the Bohr magneton and ν and H are defined previously. The g typically depends on the relationship between magnetic field vector and the orientation of the defect under observation. It is essentially a second rank tensor. (Weil et al, 1994)

Our SDR measurements were made at room temperature using a homemade SDR spectrometer utilizing a Resonance Instruments 8300 X-band (~9.5GHz) microwave bridge, a Varian Century Series 4 inch electromagnet, a Resonance Instruments TE_{102} microwave cavity, and a SR530 and Ithaco 393 lockin amplifiers. The g values were calibrated with ESR measurements on 15N nitroxide 4-oxo – 2,2,6,6 tetramethylpeperdine – d16, I-15N-1-oxyland and a (Bruker-Biospin) weak pitch standard.

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The MOSFETs used in the study were fabricated by Cree Corporation and are planar lateral 4H SiC n channel devices with ~ 70nm silicon oxide-nitride (ono) gate stacks fabricated on 3 to 5 µm of epitaxially grown p-type SiC. The gate stacks are composed of 10nm high quality thermally grown SiO_2 followed by a ~ 60nm silicon nitride layer deposited by low pressure chemical vapor deposition, then oxidized in a wet ambient to form the top 5 to 10 nm of SiO_2. The BJTs used in the study are also fabricated by Cree Corporation. We performed our measurements on 4H SiC npn BJTs. These devices consist of a 15 µm thick n-type collector doped at 4.8×10^{15} cm^{-3}, a 1 µm thick p-type base doped at $2 \times 10^{17} cm^{-3}$, and a 1.5 µm thick n-type emitter doped at $3 \times 10^{19} cm^{-3}$. The p-type dopant is aluminum and the n-type dopant is nitrogen.

Representative SDR results from 4H SiC MOSFETs are illustrated in Figures 1, 2, and 3. Figure 1 shows both a relatively narrow low-gain trace and a wider high-gain trace. The narrow trace shows that the SDR is dominated by a narrow line at g = 2.0023 with broad, strong closely-spaced side peaks, shoulders on the centerline, and weak distant sidepeaks.

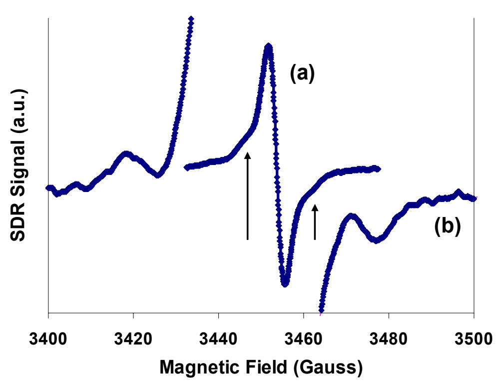

Figure 1(a) – Representative narrow SDR trace. Notice the strong central line with broad shoulders (indicated with arrows), which are almost certainly due to hyperfine interactions with second neighbor ^{29}Si sites **(b)** High-gain SDR trace with clearly visible smaller amplitude sidepeaks, which are almost certainly due to hyperfine interaction with nearest neighbor ^{13}C sites.

Figure 2 shows a series of plots of the g value of the central part of the SDR spectrum plotted versus the orientation of the magnetic field relative to three perpendicular axes of the transistor. Note that the g value is independent of orientation. The isotropic g is a strong indication that the defect is of high symmetry. As discussed elsewhere (Dautrich et al., 2006) the isotropic g and the pattern of strong broad closely spaced sidepeaks plus more distinct weak sidepeak strongly indicates the spectrum is almost certainly due to a silicon vacancy center. SDR measurements versus transistor gate voltage are shown in Figure 3. They strongly indicate that the defect is distributed in a pattern which is most highly concentrated at the SiC/SiO_2 interface, but which clearly extends beyond the interface to the bulk of the SiC.

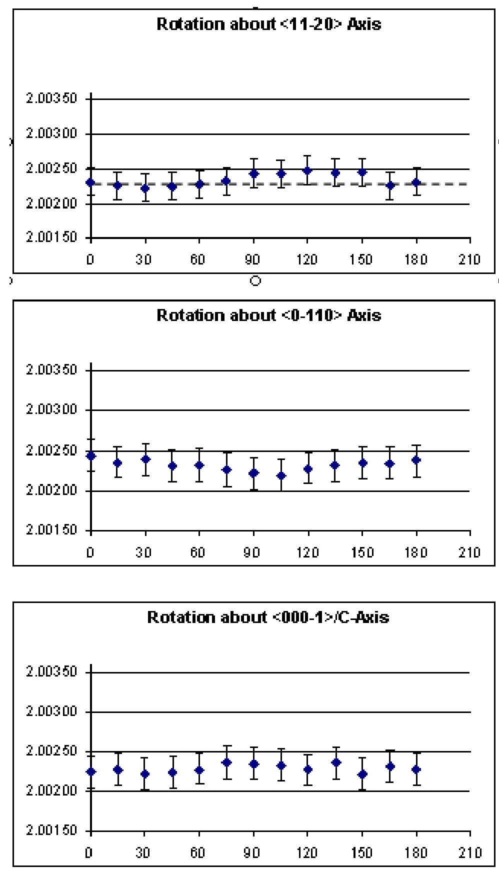

Figure 2 – g-maps obtained by rotating a 4H SiC MOSFET device about three perpendicular axes within the magnetic field.

We know that this is so because the SDR signals are not extinguished by either a large positive or a large negative gate voltage. The large positive gate voltage populates the SiC/SiO_2 interface with only electrons. A large negative voltage populates the interface with only holes. With only one sign of charge carrier present, electron hole recombination is clearly impossible at the interface, yet the SDR signal (known to be caused by recombination) does not completely disappear. This can only be possible if significant densities of these defects are present in the "bulk" of the SiC below SiC/SiO_2 interface.

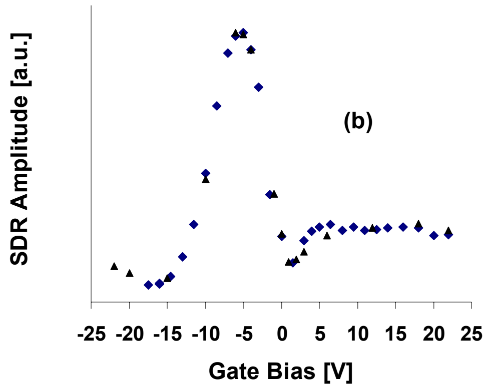

Figure 3 – SDR amplitude versus gate bias is peaked at V_G = -6 volts, but the signal remains at large biases corresponding to accumulation and inversion, where only one sign of charge carrier is present precisely at the interface. Thus the recombination centers detected under such biasing conditions must be from the depletion region beneath the interface.

Representative SDR results on a 4H SiC BJT are shown in Figures 4 and 5. Figure 4 shows a representative SDR trace with a g = 2.0026, it is broader than the MOSFET trace of figure 1 and does not have the obvious shoulders of the MOSFET curve. The SDR results indicate that the BJT defect is also almost certainly intrinsic defect of high symmetry (Cochrane et al, 2006).

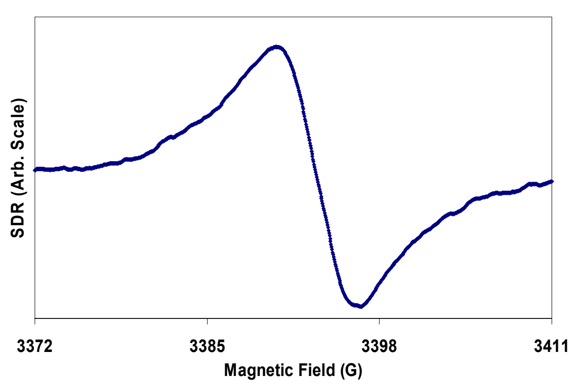

Figure 4 – This figure illustrates a narrow SDR trace of a 4H SiC BJT. This signal is approximately 4G wide.

Figure 5 illustrates a plot of this BJT signal as a function of base-to-collector (forward) bias. The top figure illustrates a first order calculation of the SDR versus voltage response expected from a uniform distribution of recombination centers in the space charge region of the junction. The agreement between theory and experiment is fairly good. The result demonstrates that we are observing an important (probably dominating) recombination center in these devices.

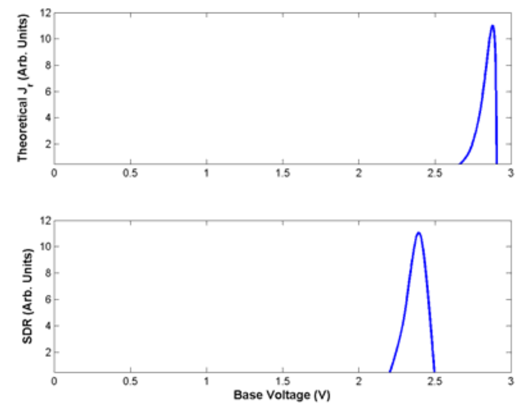

Figure 5 – This figure shows the plots of theoretical recombination current (1st order approximation) and the SDR amplitude as a function of junction voltage. The top plot represents the theoretical recombination current while the dotted line represents the measured SDR amplitude as a function of bias voltage.

Conclusions

The results presented here are a representative cross section of results which have been and continue to be obtained on a wide range of devices prepared by Cree Corporation. The goals of our study are: (1) to develop a fundamental understanding of the physics and preprocessing chemistry of the performance limiting defects and (2) to utilize this understanding to improve the performance and reliability of these SiC based devices to the extent that they will be useful to the US Army in hybrid electronic vehicles, power switches, etc.

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